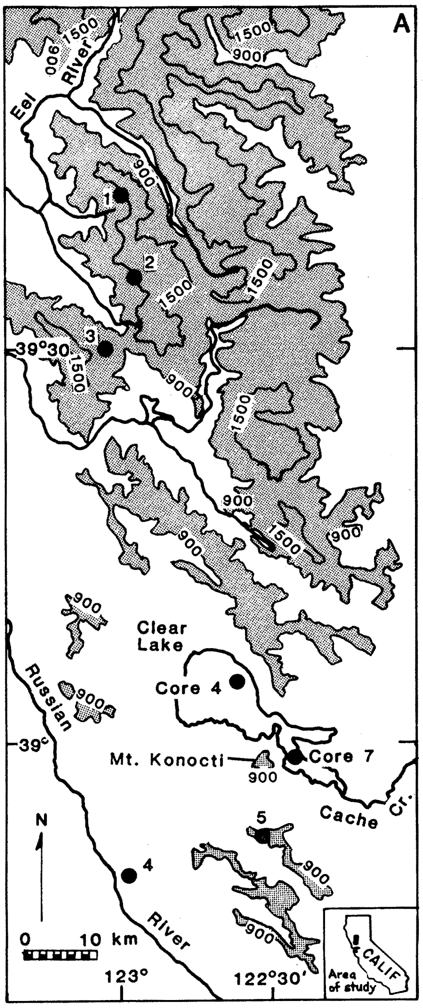
Reports

Temperature and Precipitation Estimates Through the Last Glacial Cycle from Clear Lake, California, Pollen Data

Abstract. *Modern pollen surface samples from six lake and marsh sites in the northern California Coast Ranges establish a linear relation between elevation and the oak/(oak + pine) pollen ratio. Modern temperature and precipitation lapse rates were used to convert variations in the pollen ratio into temperature and precipitation changes. Pollen data from two cores from Clear Lake, Lake County, California, spanning the past 40,000 and 130,000 years were used to estimate temperature and precipitation changes through the last full glacial cycle. The maximum glacial cooling is estimated to be 7° to 8°C; the last full interglacial period was about 1.5°C warmer than the Holocene, and a mid-Holocene interval was warmer than the present. The estimated precipitation changes are probably less reliable than the estimated temperature changes.*

Adam *et al.* (*1*) described a continuous pollen sequence covering the past 130,000 years from Clear Lake in the northern California Coast Ranges (Fig. 1A) but interpreted climatic fluctuations recorded in that core only qualitatively. Here we develop climatic transfer functions based on modern pollen surface samples from small lakes and marshy sites in the Coast Ranges and on modern temperature and precipitation data and then use these transfer functions to interpret the Clear Lake fossil pollen record in terms of temperature and precipitation changes during the last glacial cycle. Figure 2 summarizes the dating of the Clear Lake pollen records (*1, 2*).



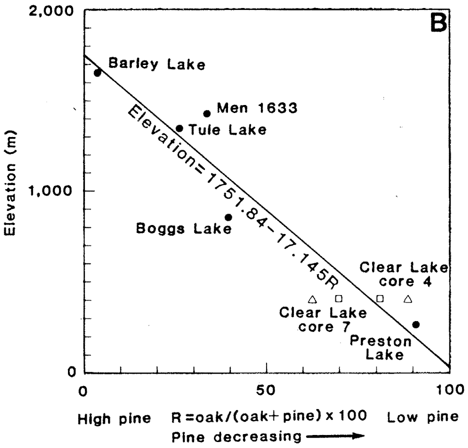


Fig. 1. (A) Locations of modern pollen surface samples used to derive the regression equation. Numbered sites are as follows: **1**, Men 1633 (California Archeological Site Survey designation; our sample came from the surface of a spring mat adjacent to the site); **2**, Barley Lake; **3**, Tule Lake; **4**, Preston Lake; and **5**, Boggs Lake. Elevations above 900 m are shaded. (B) A graph of *R* values plotted against elevation for modern pollen samples (dots) and top and near-top samples from Clear Lake cores 4 and 7 [squares and triangles, respectively; see (A) for locations]; top samples from cores 4 and 7 were not used to determine the regression line.

The transfer functions developed here differ from those used to infer temperature and precipitation histories for the western Olympic Peninsula (*3*), the Puget Lowland (*4*), and southwestern British Columbia (*5*). Those studies were based on the use of modern climatic values derived from data from 43 coastal stations, where the ocean exerts a strong buffering effect on the climate. Away from the coast, however, climatic stations are not so common and generally are located in valley bottoms, where cold-air drainage patterns can influence temperature and rain-shadow effects in the lee of mountains influence precipitation. These effects are well illustrated by a transect of climatic data across the Coast Ranges through the Clear Lake basin (*6*).

Relations between modern pollen samples and modern climatic data must be established before fossil pollen assemblages can be assigned climatic values. Clear Lake is the largest (160 km^2) lake in the northern Coast Ranges; as a pollen trap it has no modern analogs at other elevations. Thus it is not possible to obtain modern pollen samples directly comparable to the fossil samples. Because other large lakes cannot be sampled, we used pollen samples from the mud-water interfaces of small lakes and marshes in the vicinity of Clear Lake (Fig. 1A). Our fossil pollen samples, from deposits in a large lake, represent the integrated response of the regional vegetation surrounding the lake, whereas our surface samples from smaller lakes and marshes represent primarily local vegetation.

Within the range of elevations we sampled, a well-defined negative linear relation exists between elevation and the oak/(oak + pine) ratio, *R*. In Fig. 1B values of *R* are plotted against elevation. Only modern pollen surface samples are shown, except for the Clear Lake samples described below. The top samples from the two Clear Lake cores (triangles in Fig. 1B) show rather large departures from the linear relation displayed by the other surface samples, as well as from the Holocene samples beneath them. These departures probably reflect vegetational disturbance wrought by agricultural and recreational developments around the lake. To avoid the effects of this disturbance, we plotted the next lower sample in each core (squares in Fig. 1B), which should be less affected by recent cultural disturbance. This appears to be so; R values for both these samples are nearer to what would be expected from the samples from other sites. Therefore, we have used these two near-top samples, rather than the top samples, to represent modern conditions for their respective cores.

Using the near-top samples from cores 4 and 7 (squares in Fig. 1B), we found that the resulting least-squares equation was

$$\text{elevation} = 1751.84 - 17.145R \qquad (1)$$

with the standard deviation of the slope equal to 2.22 and elevation given in meters.

In terms of Eq. 1, the top sample from core 4 appears to come from an elevation of 227 m, or about 177 m below the modern lake surface, whereas the top sample from core 7 appears to come from an elevation of 685 m, or about 281 m too high. When the near-top samples are used, these disparities decrease to 41 m too low and 148 m too high, respectively.

We explain the disparity between the values of R for cores 4 and 7 in terms of the locations of the sites and the surrounding topography and vegetation. Core 4 is from the main basin of Clear Lake; the periphery of the main basin consists mostly of low ground or relatively steep slopes with a southern exposure. Core 7 is from the smaller Highlands Arm of the lake, which is bordered on the west by Mount Konocti, over 900 m above the lake. The north slopes of Mount Konocti provide a protected environment for coniferous forest normally restricted to higher elevations. We infer that pollen from this area is relatively more important in core 7 than in core 4 and generates R values lower than those for core 4.

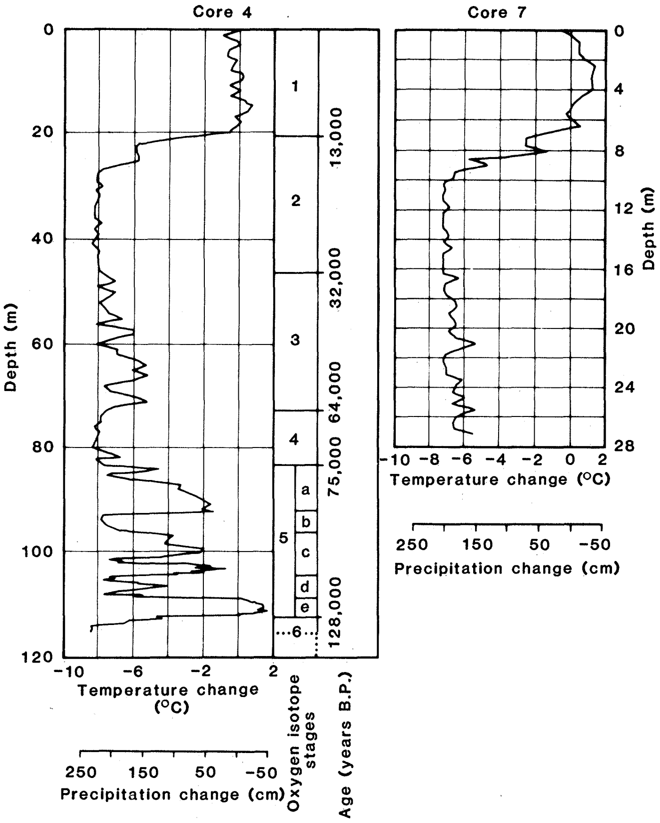


Fig. 2. Reconstructed temperature and precipitation changes from modern values through the last glacial cycle plotted as a function of depth for Clear Lake cores 4 and 7. Oxygen isotope stages and ages follow Shackleton (*17*) and Shackleton and Opdyke (*18*, *19*) and apply only to core 4. Ages [in years before present (*B.P.*)] are from (*19*).

We assume that the Clear Lake pollen record reflects changes in both temperature and effective moisture. Data from the Clear Lake area are insufficient to permit the development of an accurate precipitation lapse rate. Precipitation generally increases with altitude, but rain-shadow effects are also present. The average precipitation lapse rate in the Clear Lake area is at least 170 mm per 100 m, and the lapse rate itself also increases with elevation (*6*). We do not know how to treat this varying lapse rate; it could be considered a function of either elevation or the amount of precipitation, with varying effects on the interpretation of the fossil pollen data. We have therefore used a simple linear lapse rate of 170 mm per 100 m in our calculations.

To arrive at temperature estimates for the Clear Lake cores, we applied Eq. 1 to the fossil pollen counts for pine and oak (*7*) to calculate a "fossil elevation" for each sample. These values were converted to elevational displacements by subtraction from the value for the modern reference sample, and then to temperature and precipitation changes by multiplication by lapse rates of − 0.6°C per 100 m and 170 mm per 100 m, respectively (*6*), so that a 1 percent change in R corresponds to a 0.006 × 17.145 = 0.1°C change in temperature or a 1.7 × 17.145 = 29.1-mm change in precipitation. Results are shown in Fig. 2.

Both curves in Fig. 2 indicate a maximum temperature decrease of 7° to 8°C and a precipitation increase of about 2 m during the full glacial conditions that correspond to oxygen isotope stages 2, 4, and 6—an increase of roughly 300 to 350 percent above present precipitation. The difference in maximum cooling between the two sites is due to the different modern reference samples used. The zero minimum for R in both cores indicates little, if any, oak in the Clear Lake basin. The sensitivity of the results when R is near zero is open to question; because R cannot fall below zero, more extreme vertical displacements of the vegetation belts cannot be detected. Taking the uncertainty of the slope as twice the standard deviation leads to about a 25 percent uncertainty in the estimated changes. In addition, both the values and the stability over time of the lapse rates may introduce additional errors.

The curve for core 7 shows a distinct peak in the mid-Holocene that is not present in the curve for core 4. We interpret this peak to mean that the warmer and possibly drier conditions of the mid-Holocene differed enough from those of the early and late Holocene to change the local pollen rain but not enough to change the regional vegetation significantly.

The regional climatic history is shown by the core 4 record (Fig. 2). The last interglacial period (Stage 5e) was about 1.0° to 1.5°C warmer than the Holocene at Clear Lake and probably was drier as well. During the early Wisconsinan (Stages 5, a to d) five stadial intervals with climates nearly as severe as those of the full glacial periods alternated with interstadial intervals only 2° to 4°C cooler than the Holocene. Interstadials of the mid-Wisconsinan were distinctly cooler and wetter than those of the early Wisconsinan.

The Clear Lake paleotemperature calibrations correspond well to other paleotemperature records (*8*). Results of calibrations of temperature with elevation for the Holocene from Barley Lake and Tule Lake (Fig. 1A) suggest a mid-postglacial period 1.4° to 2.1°C warmer than today (*9*), which is in good agreement with the results from core 7 and with an estimate of a 1.9°C higher temperature for the mid-postglacial period from the White Mountains of eastern California (*10*). Although core 4 does not show a marked mid-postglacial warm period, this result may reflect the more generalized record it represents.

The temperature curve for core 7 also agrees with an uncalibrated temperature curve based on growth annuli of fish scales from the same core (*11*), which showed that tule perch scales from middle Holocene deposits have wider growth rings than scales from early or late Holocene deposits. This difference was interpreted as resulting from higher water temperatures during the mid-Holocene.

Equation 1 estimates a considerably greater temperature range than that obtained from deep-sea cores and coastal pollen records. Summer sea-surface temperatures were 1° to 2°C cooler and winter (February) temperatures were up to 4°C cooler along the California coast 18,000 years ago (*12*); maximum coolings of 4° to 5°C are estimated for the Tanner Basin off southern California (*13*) and for Kalaloch on the Washington coast (*3*). A 2° to 3°C change is estimated from pollen data north of Monterey Bay (*14*).

We attribute the greater temperature range calculated at Clear Lake to the much higher continentality of the site, which is separated from the Pacific by two ranges of mountains, and to the effects of coastal upwelling in minimizing temperature changes in the immediate vicinity of the coast (*14*). Work on plant debris from fossil pack rat middens from southern Nevada has yielded estimates that summer temperatures during full glacial times were 7° to 8°C cooler than at present (*15*), in agreement with our estimate.

The precipitation curves (Fig. 2) are based on the biologic responses of oak and pine to the modern climate of the northern Coast Ranges. Several theoretical considerations, including differences in the area-elevation characteristics of the various sites used for calibration and changes in atmospheric water vapor content resulting from lower sea-surface temperatures during glacial intervals, could modify these curves. Because sea-surface temperatures were lower during glacial intervals (*12*), the moisture capacity of the air masses must also have been lower, so that the winters must have been much stormier or longer than at present. However, the absence of significant amounts of spruce (*Picea*) pollen from the Clear Lake samples (*8*) implies that summer droughts persisted in the northern Coast Ranges throughout the last glacial cycle (*16*).

The reconstructed precipitation for the Clear Lake record shows a remarkably wide range, with as much as 2 m of additional precipitation during full glacial times. Our precipitation reconstruction is probably much less reliable than the temperature reconstruction and should be used with caution; we present it here because it is the best reconstruction presently available for California.

Although the transfer functions used here are not independent of each other, we believe that the available climatic data do not justify the use of more complicated techniques. Our results are crude, but they provide a better measure of past temperature and precipitation changes in the northern Coast Ranges of California than has been heretofore available.

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Neutron-Induced Fission of Uranium: A Dating Method for Lunar Surface Material

Abstract. *Volcanic glasses collected on the rim of Shorty Crater in the Apollo 17 area were formed 3.63 × 10^9 years ago. The amounts of xenon-136 produced by neutron-induced fission of uranium-235 indicate that the glasses resided on the lunar surface for about 38 million years before they were deeply buried. The glass spherules were reexcavated by the impact that formed Shorty Crater 17 million years ago, and remained undisturbed until they were collected.*

The most unusual material discovered by the Apollo 17 astronauts was an "orange soil," which constituted a 25-cm layer on the rim of Shorty Crater (110 m in diameter and 10 m deep). This was one of the few colorful spots observed on the moon. The orange color of this soil is due to a relatively high abundance of trivalent titanium. This soil is also unusual for another reason: it contains an excess of fission xenon isotopes attributable to neutron-induced fission of ^{235}U. Although neutron-induced fission components have been considered before, this sample represents, to our knowledge, the first case where the radionuclide ^{235}U can provide information on the timing of cosmic-ray irradiation.

A tube, driven 68 cm into the regolith on the rim of Shorty Crater to obtain a core, sampled a layer of homogeneous orange and, at greater depth, black glass droplets (*1*). The upper part of the core is NASA sample 74002 and the lower part is sample 74001. Most investigators of core 74001/2 agree that these glasses represent a pyroclastic deposit, probably formed by lava fountaining along the rim of Mare Serenitatis (*2*). Noble gases were extracted from 1 g of the bottom part of the core at a sampling depth of 144 g/cm^2 and were analyzed mass spectrometrically (*3*).

Noble gases have been useful for unraveling the history of extraterrestrial matter: the ^{39}Ar-^{40}Ar gas retention age